THE IMPULSE RESPONSE OF THE PINNA

by

ALLEN EDWARD ROLLAND

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ALLEN EDWARD ROLLAND
Lieutenant, United States Coast Guard
B. S., United States Coast Guard Academy
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ALLEN EDWARD ROLLAND
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ABSTRACT

Much has been written regarding the role of the pinna in hearing. A new approach is suggested whereby a synthetic pinna, or external ear, is treated as a linear system and characterized by an impulse response. The general nature of the transformation performed by the pinna is documented. Comparison is made with material published by other authors by transforming the time domain impulse responses into the frequency domain. Suggestions for further work are included.

Thesis Supervisor: James D. Bruce
Title: Assistant Professor of Electrical Engineering

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I am grateful to my wife Alma for her patience and her faith in me.

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Chapter 1

INTRODUCTION

The means by which man determines the location of a sound source has been of interest to many authors. This determination is called localization and consists of fixing the three spacial coordinates of the source, relative to one's own head. Necessary and sufficient information to accomplish localization consists of the curvature of the wave front, together with the normal to the front. Alternately, one may speak of the azimuth angle, elevation angle, and range to the source. One theory using the wave-front curvature frame of reference is based on the existence of intensity differences at the two ears. Another theory seeks to determine wave-front curvature by comparing the phases of the signals received at each ear. A third combines the two previous ideas. One feature these theories share in common is that they all ignore the pinna, or external ear. At most, they credit it with channeling the sound into the ear canal.

In a significant departure from these previously advanced theories of localization, Batteau[1] proposes that the pinna performs an important transformation on incoming sound waves. This work indicates that the pinna may provide multiple delay paths which are azimuth- and elevation-dependent. He suggests that the transformed signal is then autocorrelated in the brain. It is interesting to note that localization in elevation is disturbed by folding the top of one's pinnae down, an experimental result that the reader may quickly verify for himself. This phenomenon

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enhances the proposition that the pinna does play a role in human localization.

The objective of this thesis is to determine the nature of the transformation performed by the pinna. The pinna is to be treated as a linear physical system and its response to an acoustical impulse (described in Appendix E) is to be determined. Since the impulse response of a linear system completely characterizes that system, the pinna transformation will thus be specified in full.

An artificial pinna was molded of a material acoustically similar to a human pinna. This synthetic pinna was fitted with a Bruel and Kjaer microphone system. The microphone cartridge was situated at the entrance to the ear canal where it recorded the acoustical response of the pinna to the sound source. The pinna with microphone was molded to a dummy head to preserve a normal diffraction pattern in the vicinity of the pinna. The dummy as described is shown in Fig. 1. Construction details of the dummy and pinnae are included as Appendices A and B.

Fig. 1. The dummy head and artificial pinna.

Chapter 2

THE IMPULSE RESPONSE OF THE PINNA

2.1 Comparison of Human and Artificial Pinnae

The artificial pinnae used were cast of an epoxy resin similar, when cured, to an opaque Plexiglas. In an effort to evaluate the performance of the artificial pinnae, probe tube measurements were made on both human and artificial ears for comparison. The synthetic pinna tested was a casting of the human test pinna. Equipment used was a 1/2" Bruel and Kjaer type 4134 microphone cartridge fitted with a probe one inch long. The end of the probe tube was located at the entrance to the ear canal, and was oriented to point directly into the ear canal. The sound source was narrow band white noise driving two Bose acoustical transducers. The tests were not conducted in an anechoic chamber since only relative information was sought. Insofar as possible, all conditions were the same for all tests, and all tests were duplicated weekly for three weeks with the same results each time. The signal-to-noise ratio was at least 20 db for frequencies below 6 kcps, 10 db for frequencies between 6 and 12 kcps, and was never less than 5 db for any frequency below about 17 kcps. In all cases the standard for ideal performance was taken to be the sound pressure level at the entrance of the ear canal of the human subject (referred to free field pressure) as measured by the B&K probe tube microphone system. Free field pressure is taken to be the sound pressure recorded by the probe tube microphone apparatus with the head and pinna removed from the sound field.

In Fig. 2a, comparison is made between the sound pressure in a human pinna, and in an artificial pinna. Both ear canals were open. For this measurement, the artificial pinna was fitted with an artificial ear canal made of a 23-mm length of rubber tubing, 7 mm in diameter, closed at the eardrum end. The dimensions are from Nordlund.[10] The artificial pinna compares very well with the human pinna under these conditions even though the makeshift artificial ear canal was probably a poor acoustical model. The two curves in Fig. 2a are everywhere the same within five db, and are within two db over most of the frequency range.

A similar probe tube comparison is shown in Fig. 2b, again looking at sound pressure levels at the entrances to the respective ear canals. In this case, however, the human and artificial ear canals were blocked with clay. The end of the probe tube was situated near the centerline of the ear canal, about 1/16 inch from the clay. The differences between the two curves are again less than five db.

Although these comparisons are encouraging, and serve to show that the material used in the artificial ears is satisfactory, the most important comparison has yet to be made. That is, how closely does a synthetic pinna with its ear canal blocked by a microphone compare with a human pinna with its ear canal unblocked? The tests were made with the B&K probe tube microphone exactly as previously described. The result of this comparison is shown in Fig. 3. The two curves are in close agreement except in the range from 2.7 kcps to 6 kcps, where a difference of as much as 12 db occurs at 4 kcps. This divergence was not unexpected, for the ear canal is an acoustical device with a resonant frequency of about 3 kcps.[17] It would be unreasonable to expect the artificial pinna,

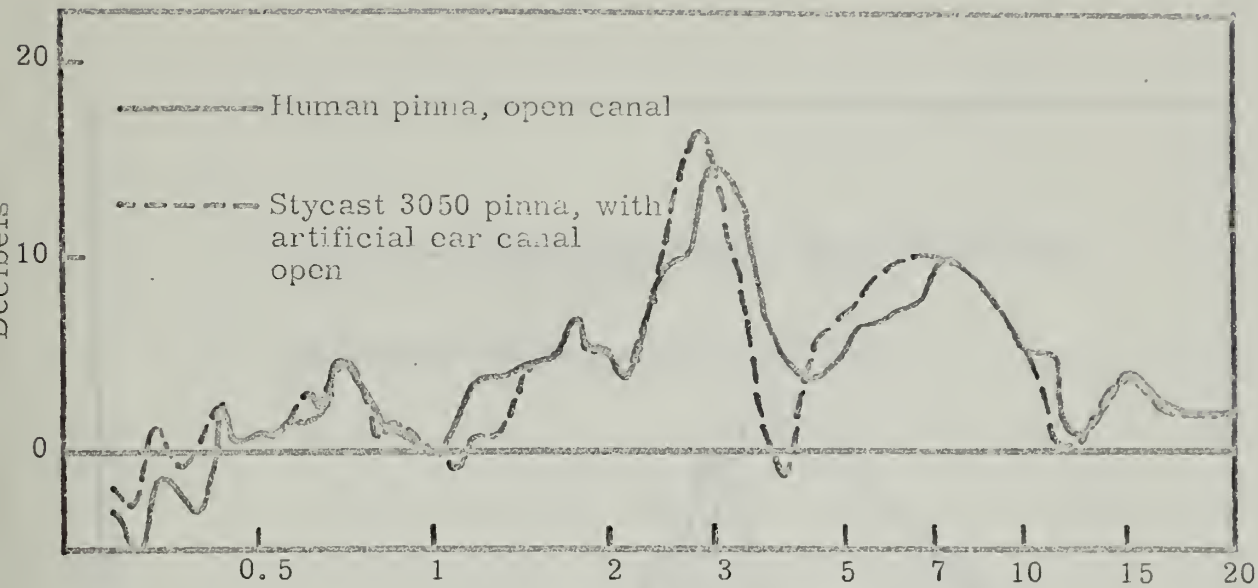

Fig. 2a. Sound pressure level at entrance to ear canal vs. frequency (kc).

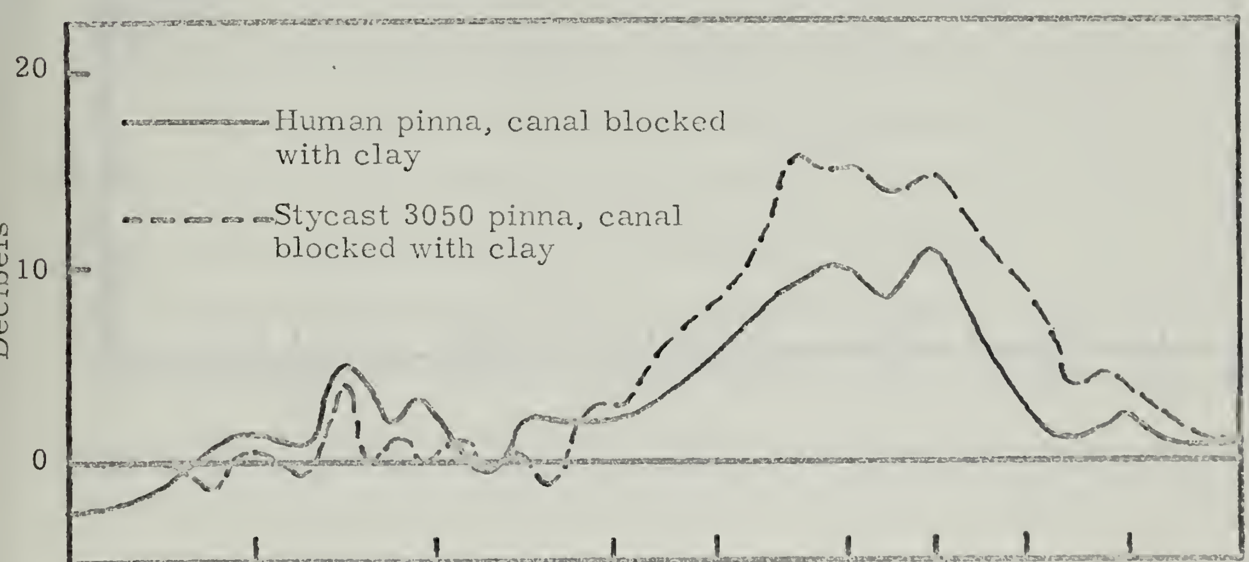

Fig. 2b. Sound pressure level at entrance to ear canal vs. frequency (kc).

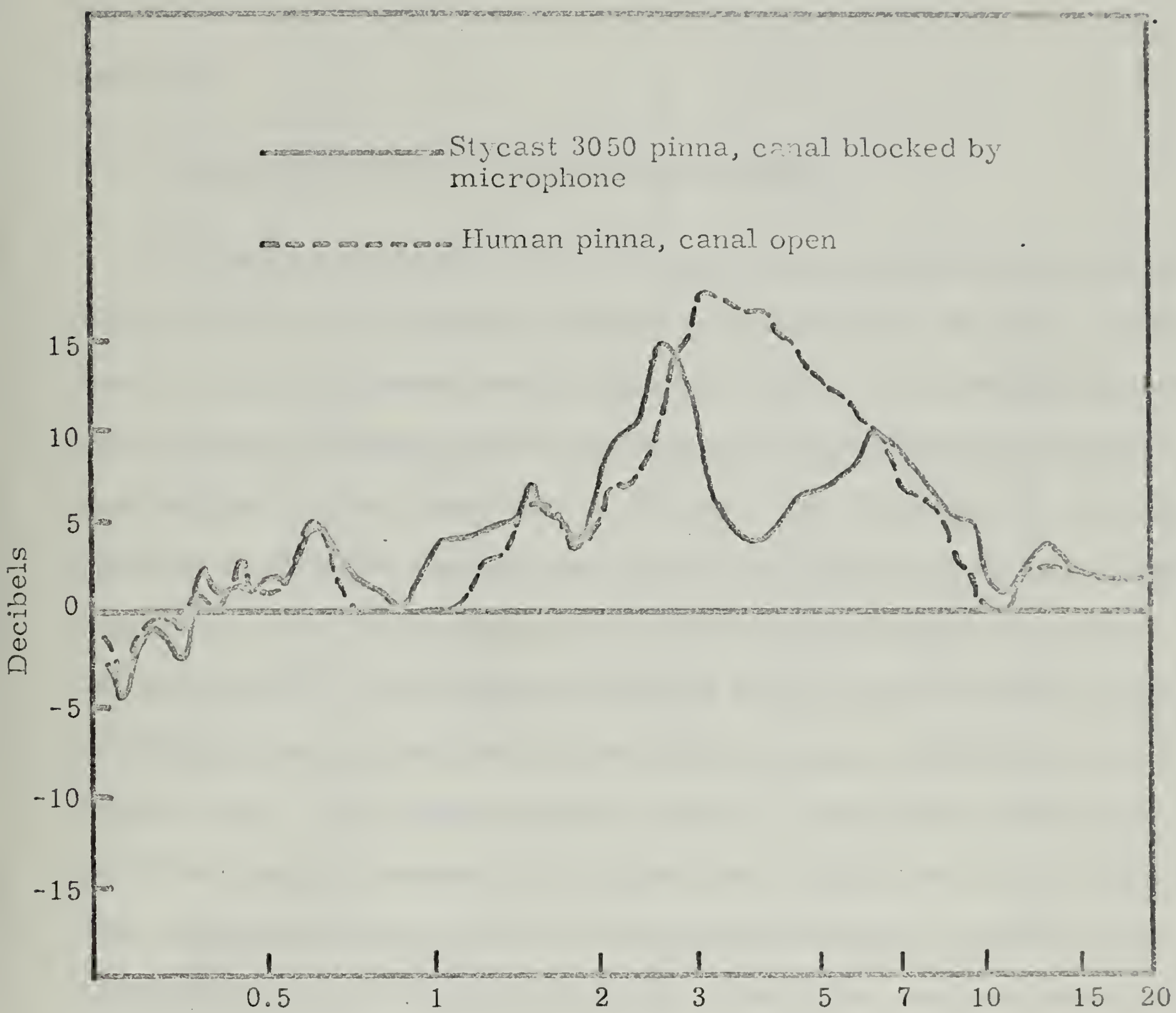

Fig. 3. Sound pressure level at entrance to ear canal vs. frequency (kc).

with its ear canal blocked by a microphone, to perform as if the microphone was not present. However, the differences between the two curves of Fig. 3 are not great, especially outside the 2.7 to 6 kcps band, and it was felt that meaningful results could be obtained within this very real limitation.

2.2 Impulse Responses of Four Artificial Pinnae

The design and construction of the apparatus used in the basic experiment of this thesis is outlined in detail in Appendices A, B, and C. A schematic of the experimental setup is given in Fig. 4. The integration step shown there is necessary since the electrical spark discharge produces an acoustical doublet rather than an impulse. See Appendix E. As a preliminary check on the characteristics of the measuring equipment, a bare microphone (i.e., microphone less artificial pinna) impulse response was determined. The technique employed was to open the shutter of the oscilloscope camera and wait for the spark to occur, producing an oscilloscope trace. The shutter was then closed. The resultant photograph shows the impulse response of the apparatus, in this case with no pinna. This response was seen to be an impulse (flat spectrum magnitude over the frequency range 100 cps to 20 kcps). Therefore, the conclusion was drawn that the apparatus could be expected to accurately determine the impulse response of the artificial pinnae. That is, the experimental results would not be significantly altered by the measuring and recording apparatus. When the distance between the spark gap and microphone was halved to three feet, the impulse response of the system remained an impulse, but now with an area twice the previous area. This supported

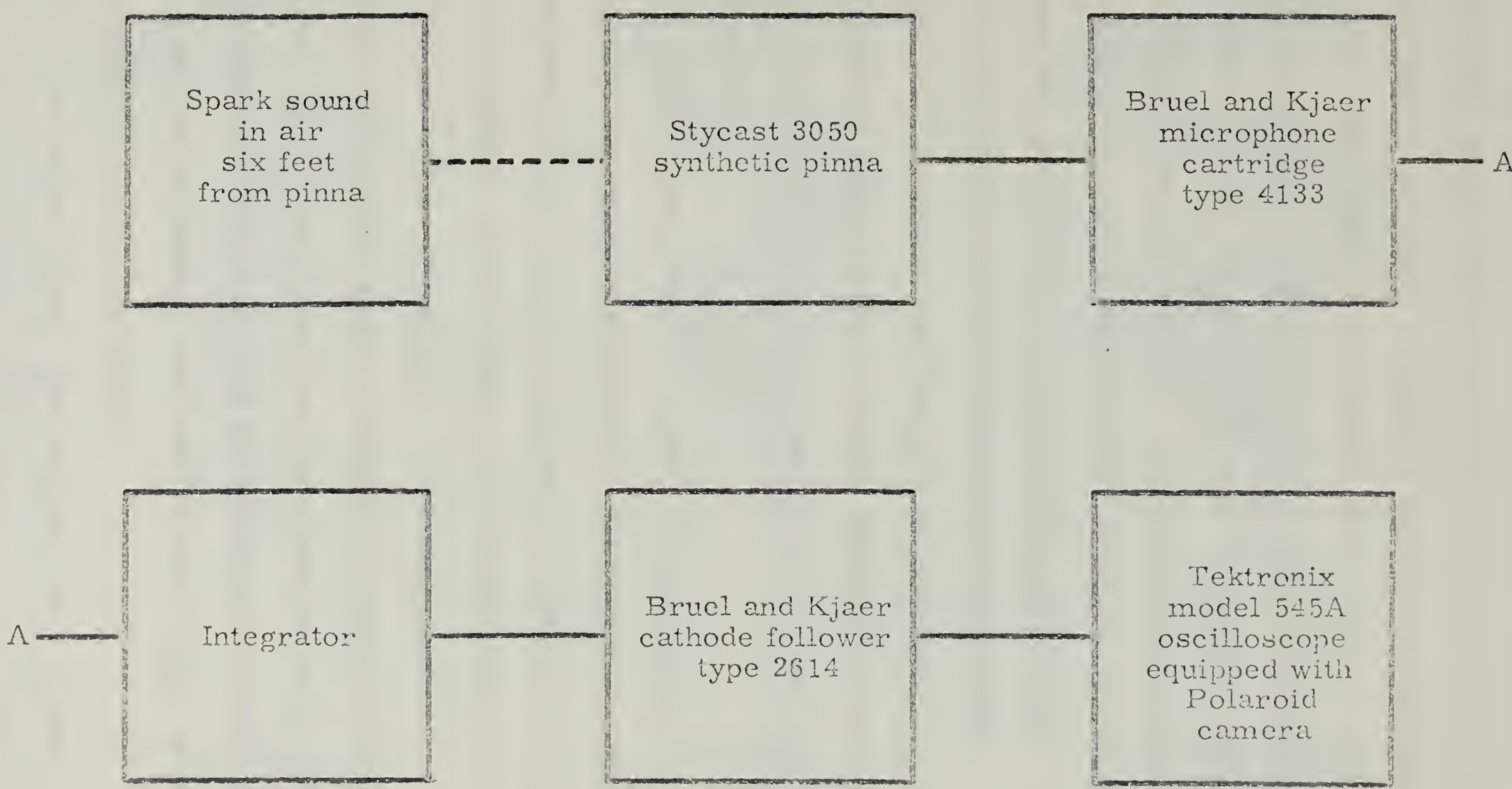

Fig. 4. Block diagram of basic experiment.

the earlier assumption that the system would be linear.

The major experiment was now conducted. In succession, four different right-side pinnae were fitted in place on the dummy, with the microphone diaphragm situated where the entrance to the ear canal would normally be located. Impulse responses were found at each of six different azimuths: 0, 45, 90, 180, 270, and 315 degrees, where zero degrees is straight ahead and 90 degrees is to the dummy's right. Three different elevations were used, +30, 0, and -30 degrees. Each of the impulse responses thus obtained was recorded photographically. See Figs. 5 and 6 for reproductions of the oscilloscope photographs. A pantograph was employed to transfer each trace from photograph to paper, using a scale expansion factor of three to one. Signal-to-noise ratios varied from about 14 db to about 30 db, being limited by the presence of the integrator in the system.

Note that for each azimuth tested, the four individual pinnae had remarkably similar impulse responses. Although the vertical amplitude of each has been scaled to give a uniform presentation, it may be observed that axis crossings, general shape, and total duration are nearly identical for the four different subjects. That this should be so, even though the four pinnae used had basic, pronounced physical differences, probably means that future experiments may be conducted with subjects listening through pinnae not their own with no resultant mismatch. No learning period should be necessary, and results should apply in general to at least a larger class of pinna types.

The major mode in these impulse responses appears to be about 3 kcps for certain azimuths and elevations, and as much as 5 kcps for

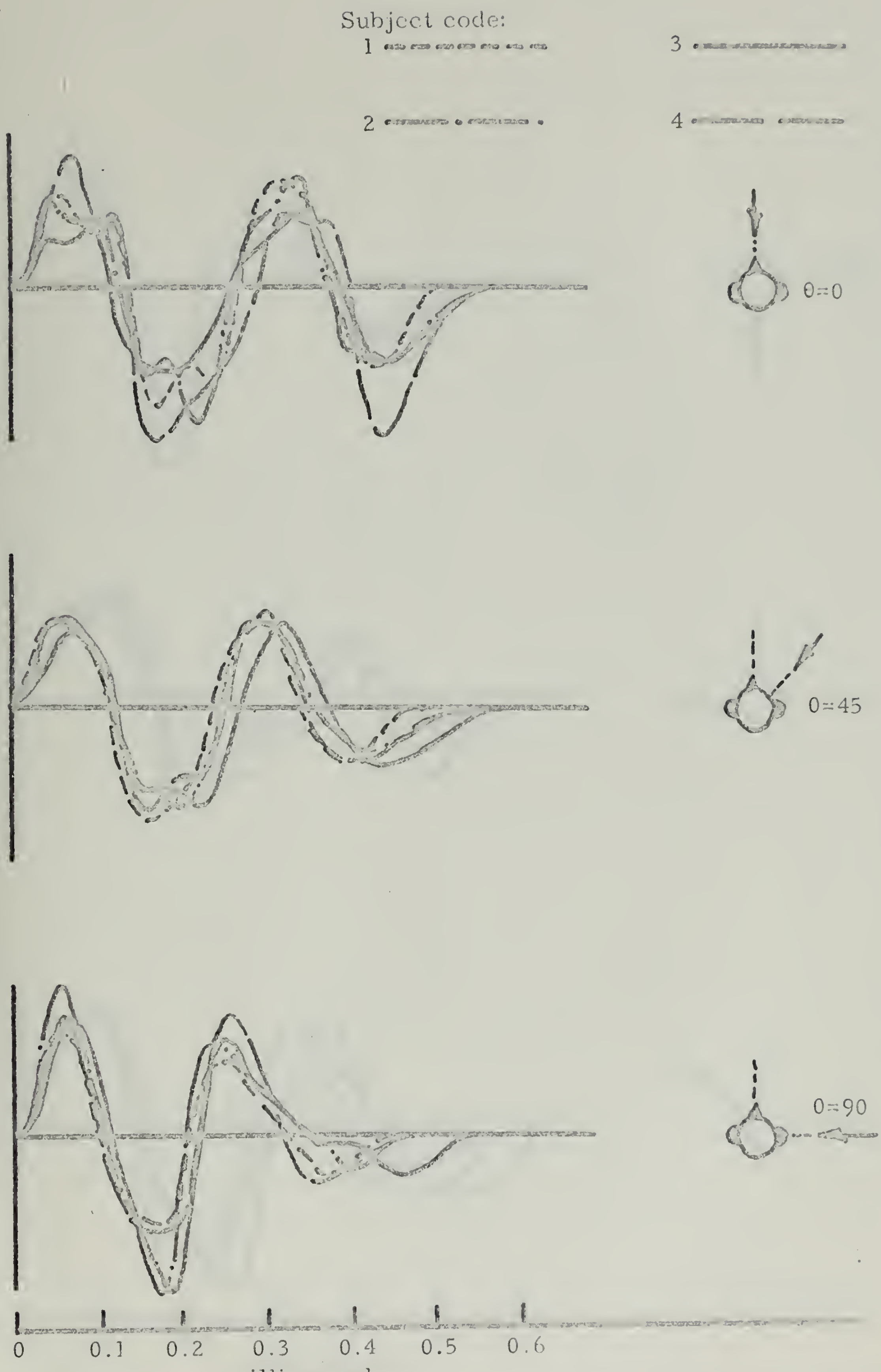

Fig. 5a,b,c. Impulse response as a function of azimuth for four subjects. Vertical scale arbitrary; each curve adjusted to same approximate amplitude. Elevation angle zero degrees.

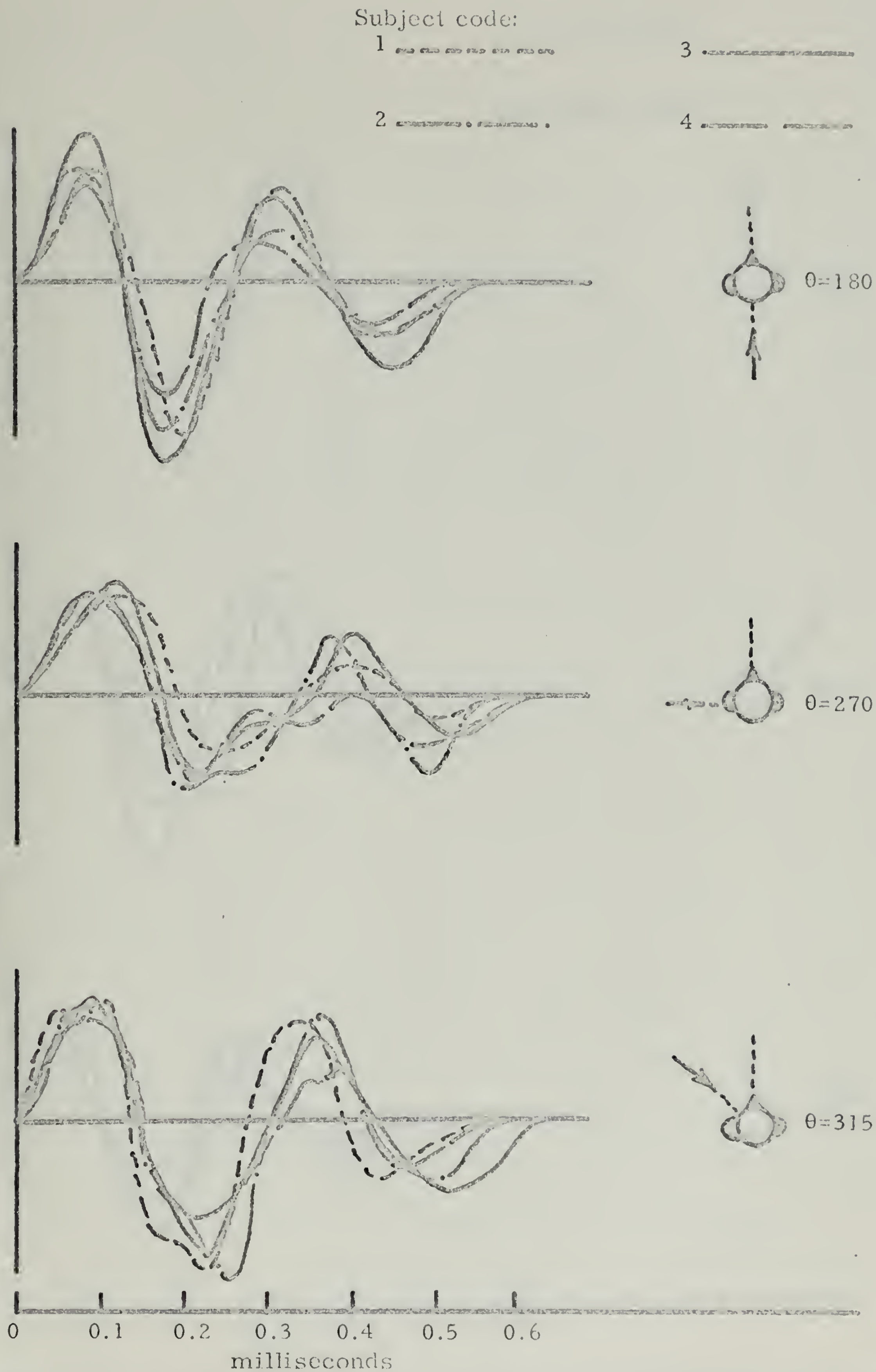

Fig. 5d,e,f. Impulse response as a function of azimuth for four subjects. Vertical scale arbitrary; each curve adjusted to same approximate amplitude. Elevation angle zero degrees.

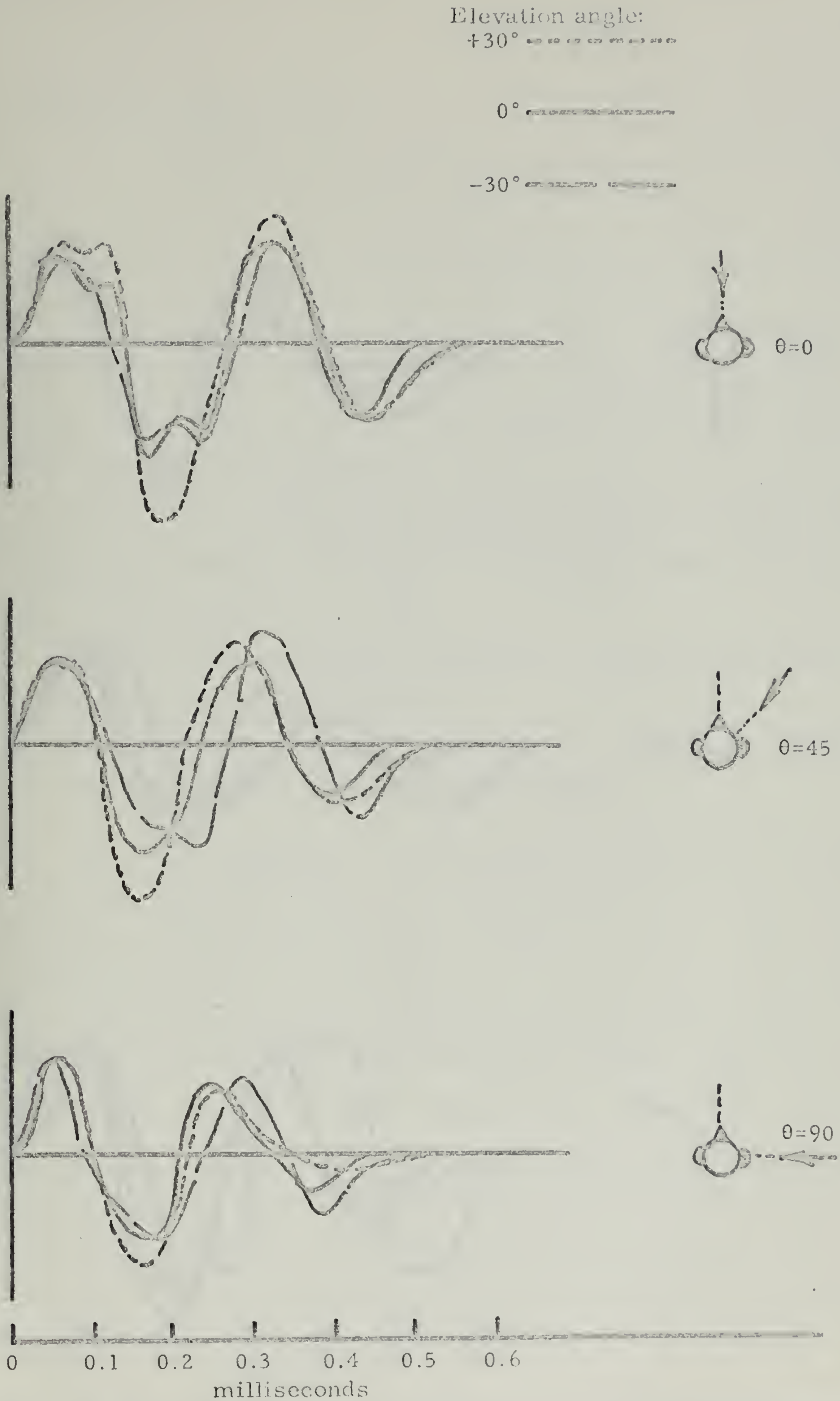

Fig. 6a,b,c. Impulse response as a function of elevation and azimuth for subject number one. Vertical scale arbitrary; each curve adjusted to same approximate amplitude.

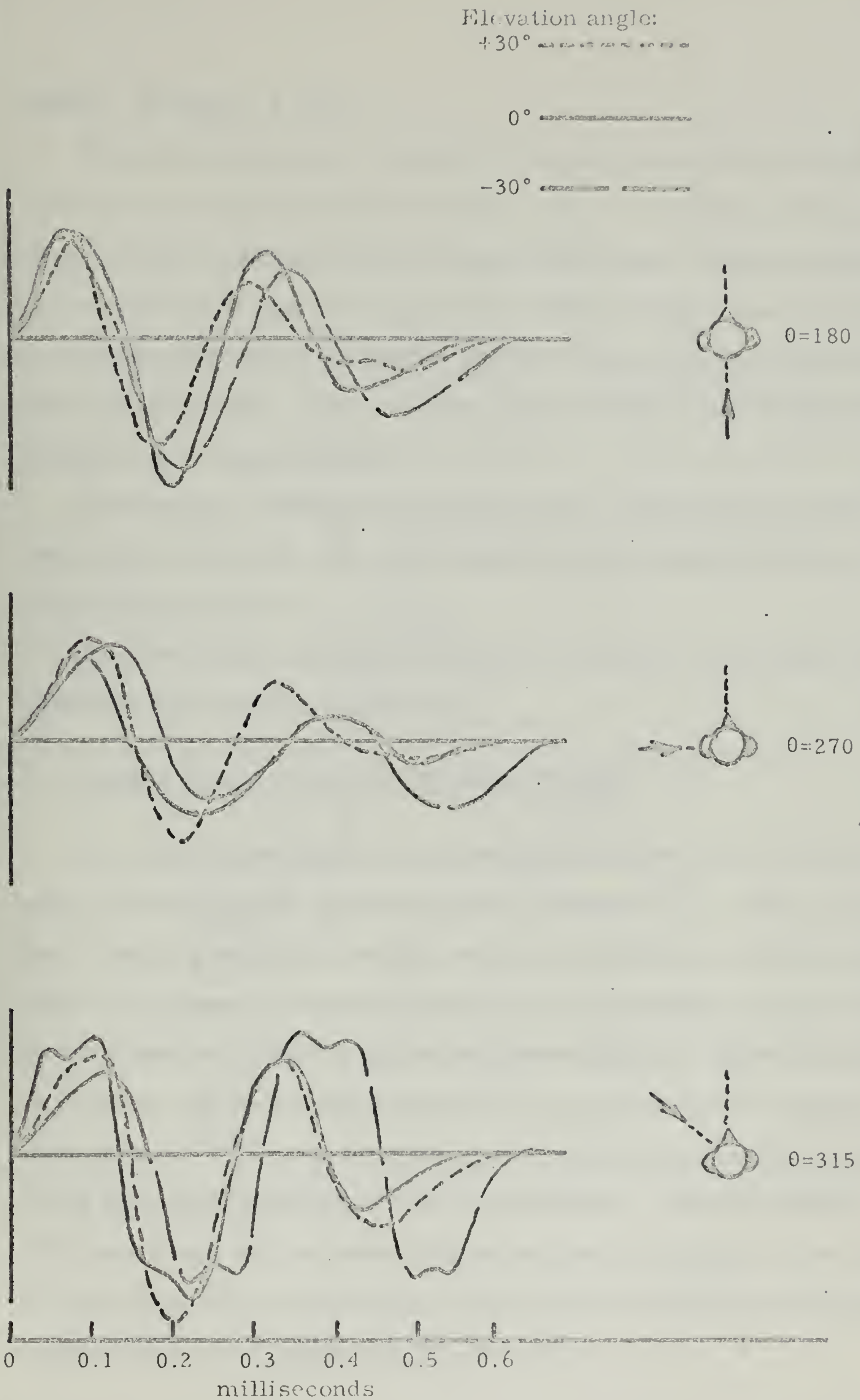

Fig. 6d,e,f. Impulse response as a function of elevation and azimuth for subject number one. Vertical scale arbitrary; each curve adjusted to same approximate amplitude.

others. See Figs. 5 and 6.

A marked dependence on azimuth was observed as shown in Fig. 7. The impulse responses of pinna number one, as a function of the six azimuths tested, are plotted with the same time scale. Vertical magnitudes are adjusted to be approximately equal, since no better comparison of magnitudes is possible (amplitude varied with the intensity of each different spark sound). Axis crossings, general shape, and duration all change with changing azimuth.

Interestingly, although the duration of the spark sound was only about 50 μs (from Fig. 14), the average impulse response lasted as long as 600 μs (Fig. 7).

Further analysis is difficult in the time domain, so the next section considers the frequency transform.

2.3 System Functions of Four Artificial Pinnae

Virtually all previously published work has been in the frequency domain (with the notable exception of that of Batteau[1,2]). Thus, corroboration of the preceding time domain results of this thesis could be found only after computing Fourier transforms of the impulse responses claimed. Such a transform would be called the system function. Here the system is the pinna and the system function is the same function of frequency that other authors[11,15] refer to as the sound pressure level at the entrance to the ear canal, referred to free field pressure. Without exception, their measurements are made with probe tube microphones. Note that all data considered in this thesis refers only to the effects of the pinna as measured at the entrance to the ear canal.

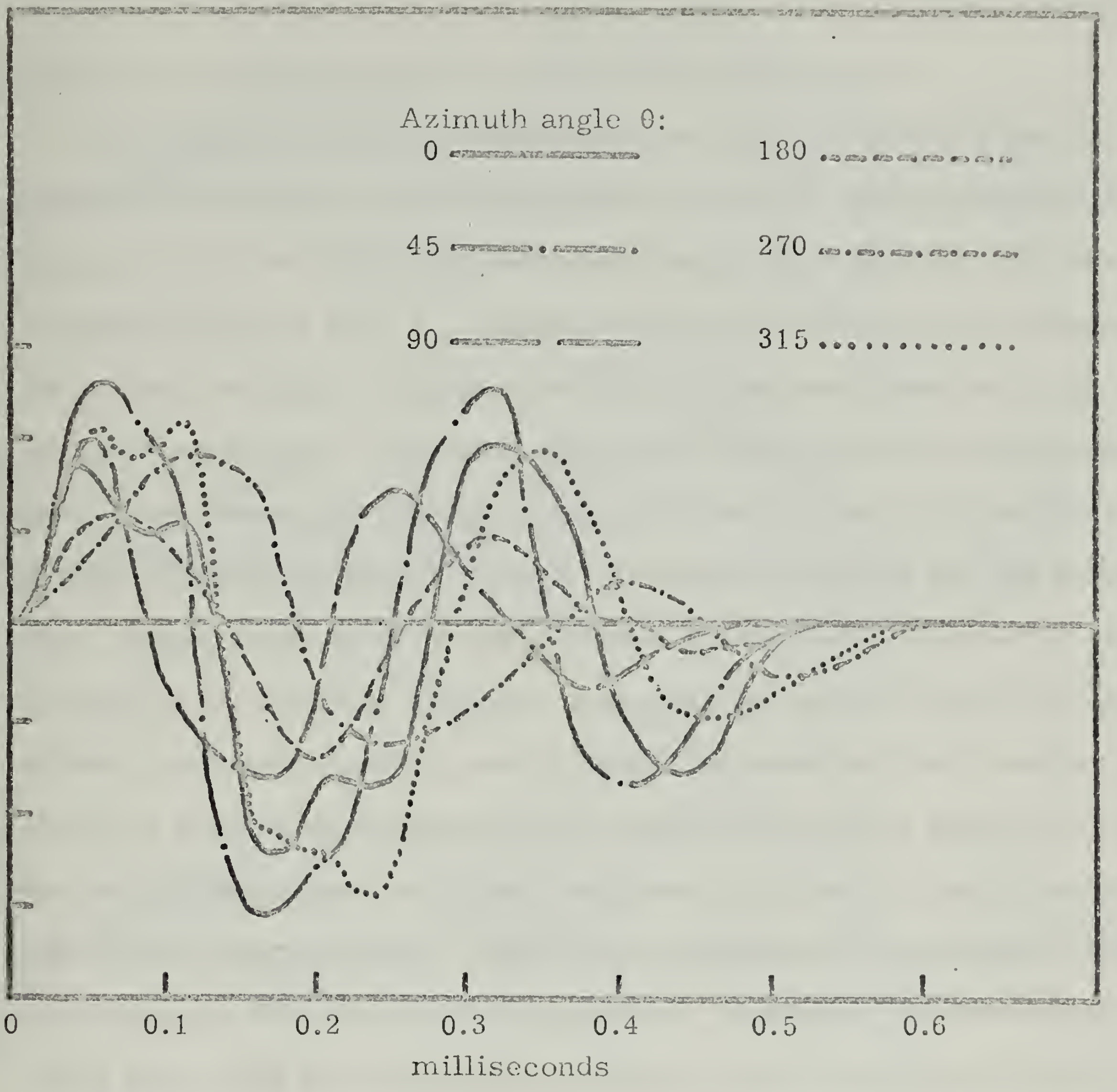

Fig 7. Impulse response as a function of azimuth for subject number one. Vertical scale arbitrary; each is adjusted to same amplitude. Elevation angle zero.

The method and the technique used to find the Fourier transforms, or system functions, are described in detail in Appendix D. A noteworthy observation on the method used, and included there, is that no frequency limitation exists in the audio range. At best, probe tube microphones are of limited accuracy above about 6 to 10 kcps.

The system functions for the right pinnae of four subjects and for six different azimuths each are plotted in Fig. 8. These functions of frequency are the Fourier transforms (magnitude only) of the impulse responses given in Fig. 5. Averages for the four subjects are shown as dotted lines in Fig. 9. These averages are compared there with the work of two other authors. The solid and broken lines show the sound pressure level at the entrance to the ear canal, referred to free field, as found by Wiener[16] (1947) and Shaw[12] (1965). The solid portion of the line is Wiener's data, substantiated by Shaw. The broken line is due to Shaw and is the average of ten subjects. All data is normalized to 0 db at 500 cps. Both Wiener and Shaw relied on probe tube microphones for their results. Note the close general agreement between the system function averages of this and the related results of Wiener and Shaw up to about 6 kcps in some cases and 8 kcps in others. The radical differences beyond these frequencies and up to 20 kcps remain unexplained. However, the point has already been made that the method utilized in this thesis is essentially free of the limitations on frequency range and sensitivity that are inherent in probe tube measurements.

Fig. 10 groups all azimuth curves for subject number one, as taken from Fig. 8. Subject one is characteristic of the other three subjects. The reduced levels of the system functions for azimuths of 270 and 315 degrees are probably due to the sound shadow cast by the head.[8]

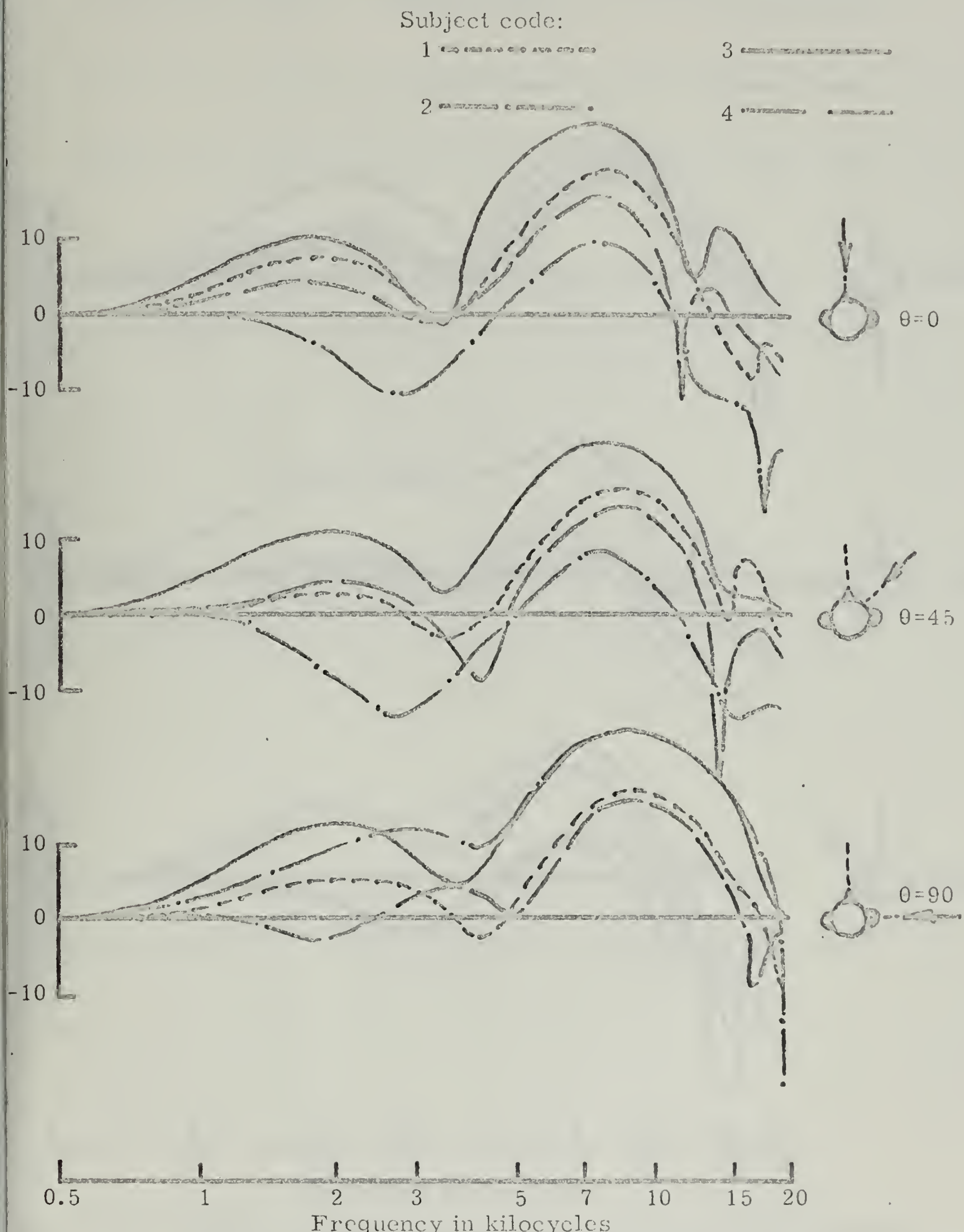

Fig. 8a,b,c. System functions as a function of azimuth for four subjects. Vertical scale in decibels. Elevation angle zero.

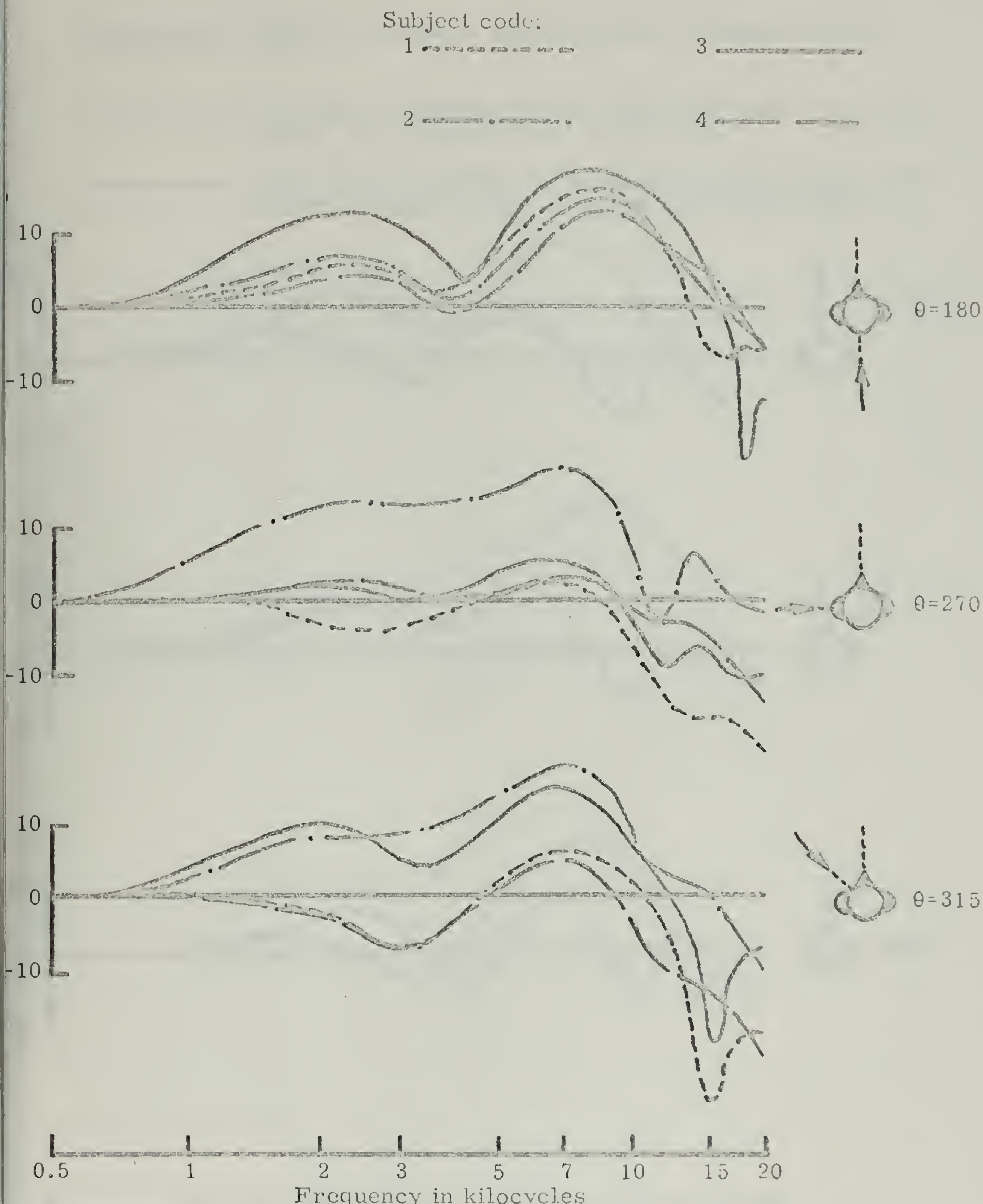

Fig. 8d,e,f. System function as a function of azimuth for four subjects. Vertical scale in decibels. Elevation angle zero.

System function of artificial pinna (average of four)

Pressure at entrance to ear canal (average of nine subjects). From Shaw's Fig. 4 (ref. 12).

Pressure at entrance to ear canal (average of six subjects). From Wiener's Figs. 2 and 3 (ref. 16).

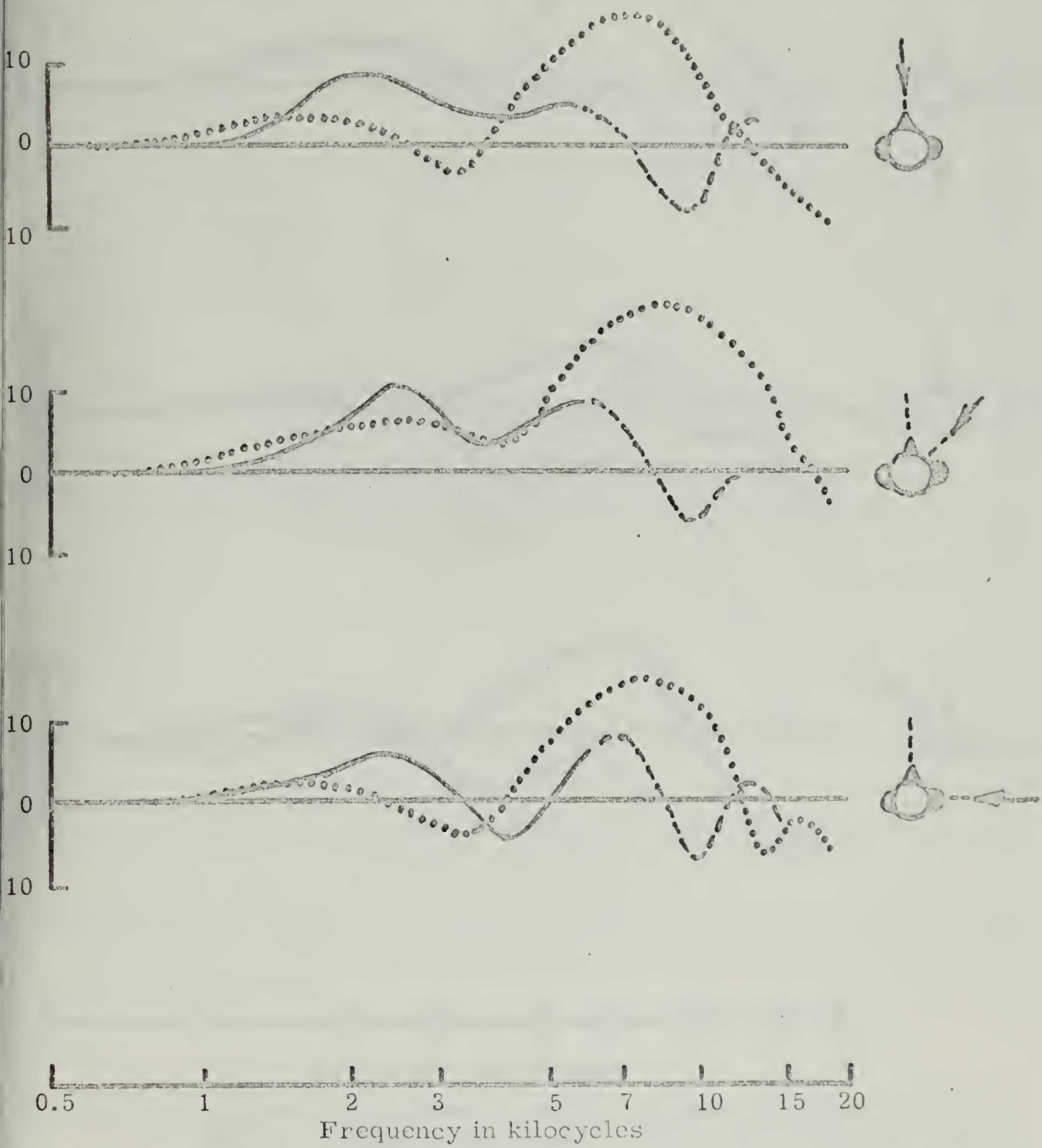

Fig. 9a,b,c. Comparisons of present author's system functions with other authors' pressure at entrance to ear canal. Vertical scale in decibels. Elevation angle zero. All curves normalized to 0 db at 500 cps.

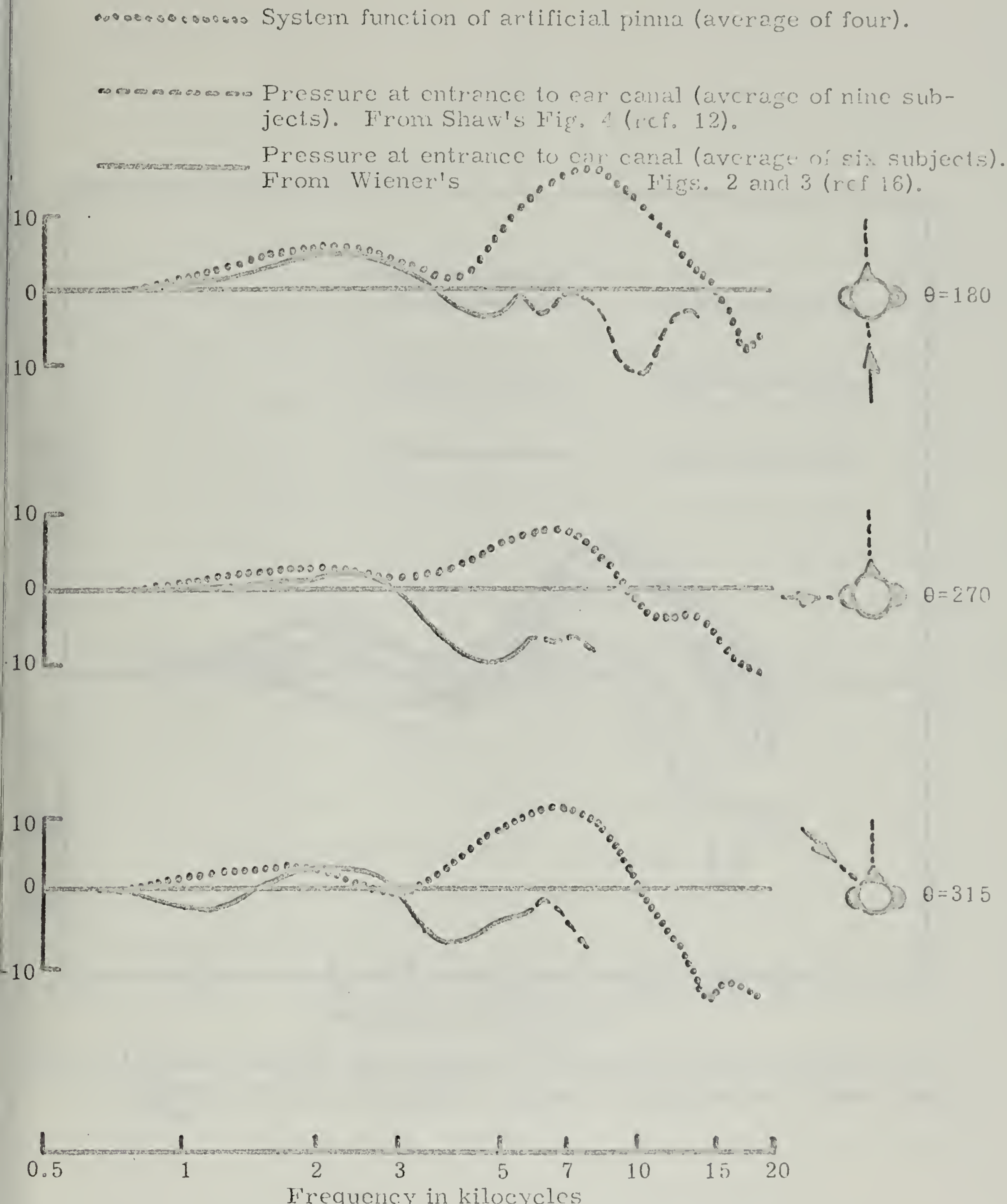

Fig. 9d,e,f. Comparisons of present author's system functions with other authors' pressure at entrance to ear canal. Vertical scale in decibels. Elevation angle zero. All curves normalized to 0 db at 500 cps.

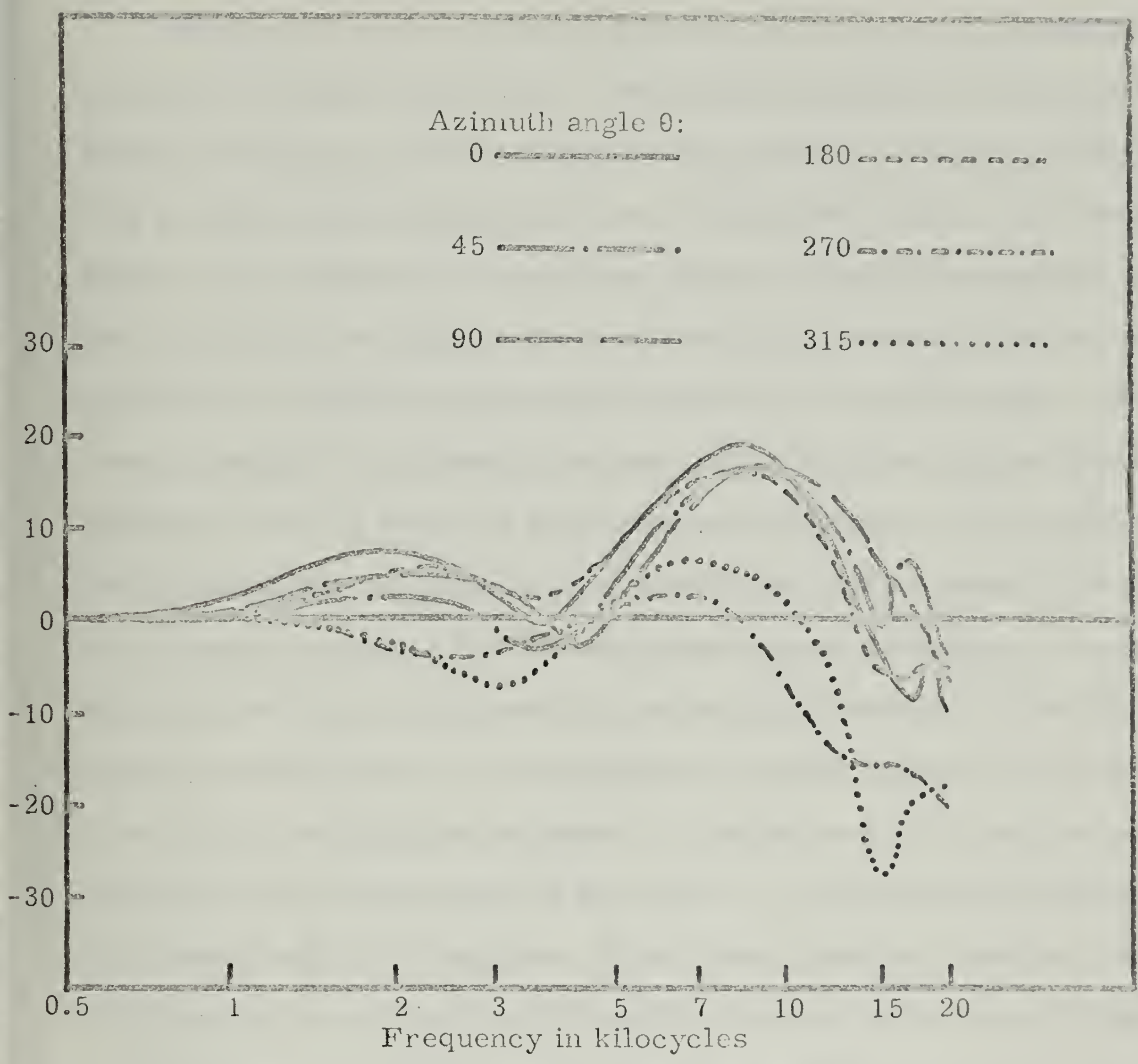

Fig. 10. System function as a function of azimuth for subject number one. Vertical scale in decibels. Elevation angle zero. Taken from Fig. 8.

Chapter 3

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

The general topics explored by this thesis do not lend themselves to obvious or easy conclusions. The impulse response of the pinna has indeed been found, and the related system functions compare favorably with previous work by other authors. The synthetic pinna used seems to be a good substitute for the human pinna, although the presence of the microphone cartridge at the entrance to the normally open ear canal disrupts the acoustical properties of the ear to a certain extent. However, although a considerable amount of data has been obtained and documented herein, no theory of localization has appeared. The proposition that the pinna has an important function in localization needs to be studied. For instance, consider the following hypothetical experiment: A subject using insertion type earphones (to prevent his pinnae from affecting incoming sounds) listens to a sound source passing through a certain network before reaching the earphones. That network is to have an impulse response such as that shown in Fig. 5b; i. e., the impulse response for an azimuth angle of 45 degrees. If the pinna plays an important role in localization, the subject should localize the sound at an azimuth angle of 45 degrees. With this result, attention would then be focused on the network with the pinna impulse response. Running tests could be made, changing the impulse response while listening. Or comparisons could be made using networks set with different impulse responses.

Time has limited the scope of this thesis to finding the impulse

response of the pinna. However, through experiments such as those mentioned above, the results produced here should serve as an important first step in the larger problem of understanding how localization is possible.

Appendix A

DESIGN AND CONSTRUCTION OF THE HEAD

Previous work by Holmes[9] in the Research Laboratory of Electronics showed that the diffraction patterns around a dummy head carved of balsa wood and covered by latex rubber are substantially those surrounding a human head. In an effort to better approximate the human head, a new dummy was constructed. The low density (10 lbs/cu. ft.) balsa wood was discarded in favor of higher density (26 lbs/cu. ft.) plastic foam. The latex rubber outer covering was retained.

The head from a department store mannequin was obtained and coated with paste wax. A latex rubber coating was then applied with a spray gun, alternating each coat with ten-minute curing periods in a 200-degree oven. The finished thickness is about 5/32 inch. After an overnight cure, the rubber mask was stripped off the mannequin head and set aside for further work.

The interior details were designed with future experiments in mind. Accordingly, adequate space is provided for different types of internally situated microphone systems. Mutual isolation of the two ears was also a consideration. Taking all problems into account, a wye of 2" ID brass tubing was chosen to form the necessary interior passages. The wye was fabricated with the arms at an angle of 45 degrees from the vertical, as shown in Fig. 11. The three sections of tubing are silver soldered together.

Proceeding to the next step in construction, the rubber mask was placed in an inverted position with the tubing in place inside it. The cu-

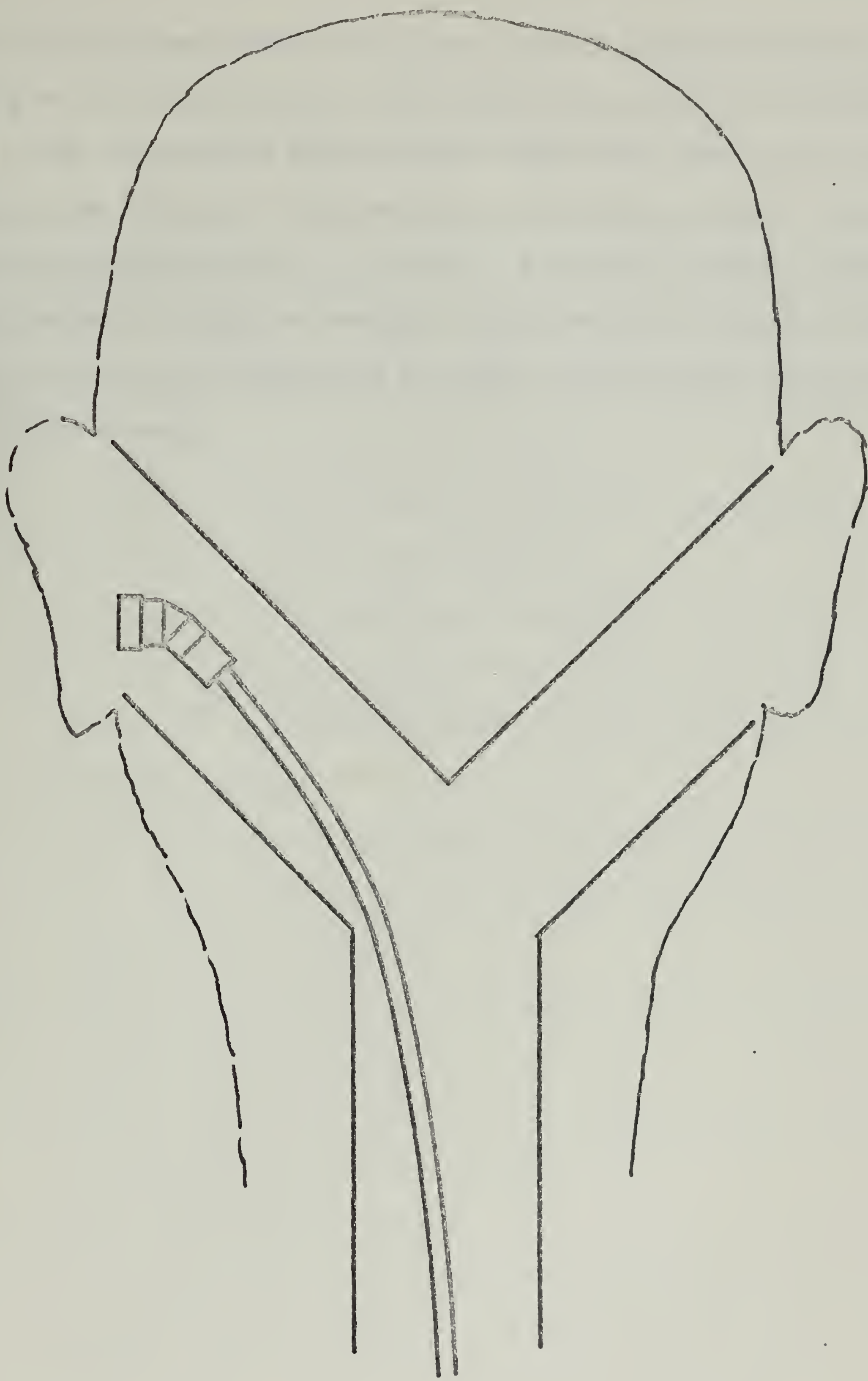

Fig. 11. Cutaway view showing the inside arrangement in the dummy. The three-conductor cable is soldered to a 45-degree angle adaptor, which is in turn fastened to the Bruel and Kjaer type 4133 microphone cartridge.

side of the mask was packed with sand to control anticipated expansion during the following operation. The mask was then filled with Eccofoam FP, a rigid polyurethane foam-in-place liquid resin, which has a bulk density of 26 lbs/cu. ft. This resin was mixed with a catalyst, which caused vigorous foaming in the mixture. A fourfold expansion took place, filling the mold. Again, an overnight curing period was required. Trimming and cutting the openings for the pinnae completed the construction of the dummy head.

Appendix B

CONSTRUCTION OF ARTIFICIAL PINNAE

The methods applicable to molding and casting the artificial pinnae used in this thesis and the selection of materials used in the process are due to Batteau.[2] Basically, a rubber mold is made of the pinna and then that mold is used to cast an artificial pinna using a suitable material. As an aid to future work, the procedure is given here:

1. Wash ear, and insert cotton in ear canal to protect same.
2. Cover hair in vicinity of ear with tape.
3. Spray ear with a mold release to facilitate mold removal.
4. Mix Dow Corning Silastic RTV 502, a room-temperature vulcanizing rubber of medium flexibility, with provided catalyst according to directions.
5. With subject's head lying horizontally, apply RTV 502 mix to ear. Technique must be gained by experience to yield a mold with no voids or air bubbles.
6. When cure is complete, in about twenty minutes, carefully strip mold from ear of subject.
7. Build up edge of mold with Dow Corning Silastic RTV 732 to facilitate the pouring of the pinna casting.
8. Spray mold with mold release.
9. Mix Emerson and Cuming Stycast 3050, an epoxy casting resin similar to opaque Plexiglas when cured, with the proper catalyst. Pour into mold. Again, only technique gained through experience can produce a good nonporous casting with no bubbles or voids.

Pinna castings were made from the right ears of four different subjects.

Appendix C

DETAILS OF THE MICROPHONE SYSTEM WITH INTEGRATOR

The Bruel and Kjaer 1/2" capacitor type microphone cartridge was selected for its excellent frequency response characteristic, its good sensitivity as compared with smaller diameter cartridges, and its conveniently small size. However, the design decision employing the brass tubing wye in the dummy created a problem because B&K does not make an adapter which permits a 45 degree bend between the microphone cartridge and its cathode follower. Accordingly, the Research Laboratory of Electronics machine shop was called upon to design and fabricate several of these 45 degree adapters. Each has three concentric conductors separated and insulated from each other by specially machined sections of Teflon tubing. During final assembly of each adapter, liberal use was made of cleaning solvents to keep out all traces of dirt. The relative location of the adapter as used in the dummy may be seen in Fig. 11.

The microphone cartridge is cushioned in Silastic RTV 732 rubber and is situated at the entrance to the ear canal. A lead sleeve surrounds the concentric rubber cushion. In the finished form, a circular area 7 mm in diameter in the center of the cartridge diaphragm is exposed to the sound pressure present at the entrance to the ear canal. The cartridge is shielded and isolated from sound pressures or vibrations from any direction other than the normal path sound follows in reaching the ear canal. The 45 degree adapter previously described was fastened to the microphone cartridge with the conventional screw threads. The

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opposite end of the adapter was connected to a one-inch diameter B&K cathode follower, type 2614, via three-concentric-conductor cable. As explained in the next paragraph, it was necessary to interpose an integrating network between the adapter and the cathode follower. This was inserted between two sections of the above mentioned cable.

Utilizing the doublet source which is described in Appendix E, one could proceed and find the doublet response of a linear system (such as the pinna is herein assumed to be), but the integrated version of such a response is more often considered. This is so, because the Fourier transform of the impulse response to be obtained is the familiar system function. This integration step could, theoretically, be performed anywhere in the system, including at the input or output. Of course, in this case the excitation cannot be integrated. Also, unless the integration network precedes the microphone cathode follower, objectionable distortion occurs there. These facts, together with the space limitations inside the dummy, required that the integration network be located after the microphone cartridge and before the cathode follower. This was done, using a circuit due to Bruce.[5]

The acoustical-electrical system in Fig. 4 was settled on as the one needed to find the desired pinna impulse responses. Before proceeding, however, the system was checked by temporarily replacing the microphone cartridge with a B&K JJ2614 and an electrical equivalent of the microphone. The JJ2614 permits an electrical rather than an acoustical input to be made to the microphone system. The electrical input chosen was a periodic train of differentiated pulses. The system, when properly set up, integrates each such differentiated pulse and yields an output pulse

train with a flat spectrum -- the same spectrum the undifferentiated input pulses had. In this manner, the system was shown to be integrating as desired, at least from 100 cps to 20 kcps. The electrical input adapter was then replaced by the B&K type 4133 microphone cartridge and fitted to the dummy head and pinna.

Scope triggering was accomplished by placing a separate microphone system slightly closer to the sound source than the six feet chosen for the source-to-pinna distance. This early pulse, received each time the spark fired, was stepped up by a transformer and used as a trigger source. This arrangement is due to Dodds.[6]

Appendix D

THE FOURIER TRANSFORM OF AN APERIODIC SIGNAL

As outlined in the text, the necessity arises to Fourier transform the aperiodic impulse responses earlier determined. To accomplish this, several methods are available. Dodds[6] utilized a computer in his work with electric spark waveform transformations, thereby employing a method which yields both magnitude and phase information. However, this process is time-consuming and tedious. Since there were some two dozen Fourier transforms to be taken, the following method (shown schematically in Fig. 12) was chosen.

In each of the 24 cases, an electronic circuit was obtained with an impulse response identical to the impulse response which was to be Fourier transformed. This was easily accomplished by using a tapped delay line two milliseconds long with variable taps of 20 microseconds each. The delay line received an input of 20 microsecond pulses from a Tektronix Pulse Generator. The desired impulse response was constructed, in this most elementary fashion, with rectangular 'building blocks' 20 microseconds long and of adjustable height. By expanding the time scale of the impulse response being duplicated, it was possible to use all 100 taps and closely approximate the original impulse response. As a visual guide during the process of setting each tap on the delay line, the shape of the desired impulse response was actually drawn on the oscilloscope face. These responses had been originally recorded on Polaroid film, so it was a simple matter to cut each photograph in two

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[illegible]

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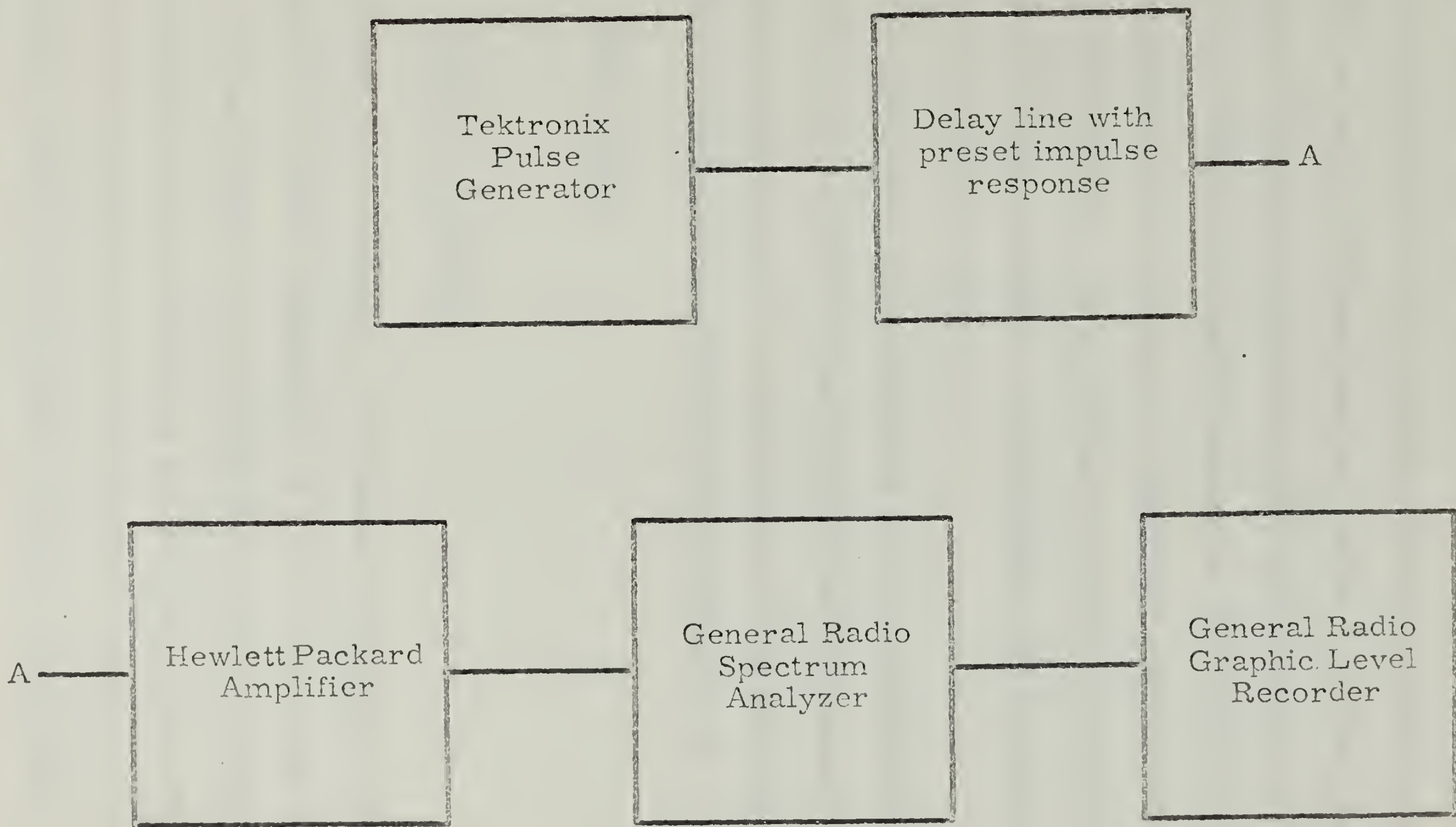

Fig. 12. Block diagram of Fourier transforming setup.

along the trace. The lower half was then used for a template to transfer the exact shape of the impulse response to the oscilloscope face. The oscilloscope was then used to monitor the output of the delay line as the taps were adjusted to synthesize the desired impulse response.

With an input of 20 microsecond pulses from the pulse generator, the output of the delay line was not just one impulse response, but a periodic train of identical impulse responses. This signal was fed to a General Radio Spectrum Analyzer and Graphic Level Recorder. The output of the level recorder was a plot (versus frequency) of the magnitude of the desired system function. Unfortunately, phase information could not be obtained using this setup.

The time scale expansion factor of 5.0 mentioned earlier, combined with a factor of 1.43 introduced by the Polaroid camera lens, gave an over-all scale factor of 7.1. This factor is the parameter "a" in the following scaling property of Fourier transforms: If

$$h(t) \longleftrightarrow H(f),$$

then

$$h(t/a) \longleftrightarrow |a|\, H(af).$$

This means that a frequency of 3 kcps on the graphic level record corresponds with an actual frequency of $3 \times 7.1 = 21.7$ kcps in the system function. The scale factor was introduced in order to allow the use of more delay line taps when synthesizing the impulse responses. An unexpected bonus was that plots on the level recorder could be terminated at the 3 kcps point instead of at 20 kcps, allowing a substantial savings in plotting time.

As a final observation regarding the system functions so obtained, it may be seen that the method has no upper frequency limit within the range of normal hearing. Since the Bruel and Kjaer microphone system used to obtain the impulse responses is practically flat to 40 kcps, and the spectrum analyzer is usable to 50 kcps, it is theoretically possible to find the system function of the pinna for frequencies up to 7.1×40 kcps = 284 kcps. This is substantially beyond the upper limit of hearing, usually taken as 20 kcps.

To illustrate these procedures, consider the simple exponential shown in Fig. 13a. This waveform is the capacitor voltage in a series RC circuit, where RC = 4×10^{-4} seconds, for an input of a unit pulse. The periodic waveform of Fig. 13b is obtained when the RC circuit input is a periodic pulse train. The Fourier transform of this periodic signal was found using the methods previously outlined, and is seen as Fig. 13c. Note the familiar shape, and the fact that the magnitude of this transform varies as 1/f for large f.

Fig. 13a. A simple aperiodic signal -- the exponential.

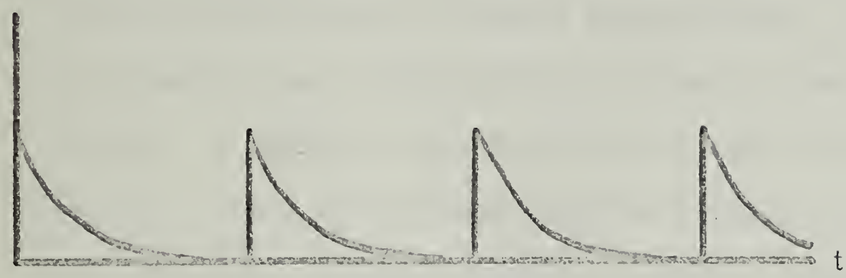

Fig. 13b. A periodic signal -- a train of exponentials.

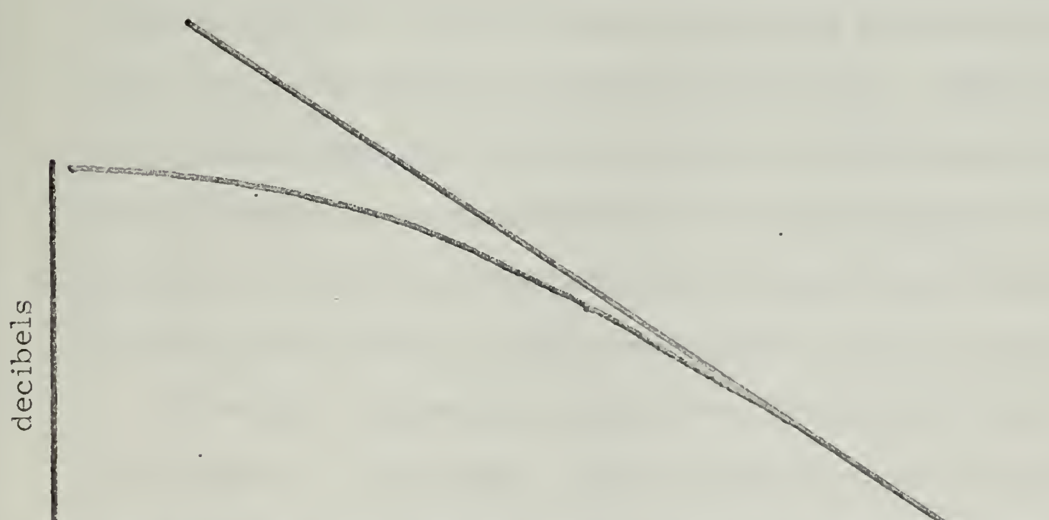

Fig. 13c. The Fourier transform of Fig. 13b. Asymptote slope is 6 db/octave.

Appendix E

THE ELECTRIC SPARK AS A SOUND SOURCE

As early as 1939, Békésy[4] noted that, of all sound sources he tried, the sound of an electric spark in air is best localized. According to Batteau,[3] for a sound to be localized when only one ear is used, the sound must be of sufficient complexity to "span" the three coordinates of space. Thus, it would appear that there is some characteristic of an electric spark that qualifies it as such a sound source. Dodds[6] has shown that the sound pressure generated by an electric spark in air is an acoustical doublet. A doublet (acoustical or otherwise) is the first derivative of an impulse, and it is well known that the impulse response of a linear system completely characterizes that system. See Fig. 14a for a reproduction of an actual spark sound waveform as taken from an oscilloscope picture. The same type of spark, electrically integrated, is shown in Fig. 14b. The magnitude of the spectrum of this resulting impulse is shown in Fig. 14c. This flat spectrum means that the sound from a spark gap in air meets Batteau's spanning requirement. Additionally, we see that a spark sound is of value as a sound source because its properties may be simply and uniquely described. This means that the results of any given acoustical experiment using the spark sound source may be ascribed to that which is being investigated, and not to the source utilized.

Therefore, the decision was made to employ the electric spark as a sound source. Accordingly, this selection made the experiments independent of the idiosyncrasies of any loud-speaker system. Also, since

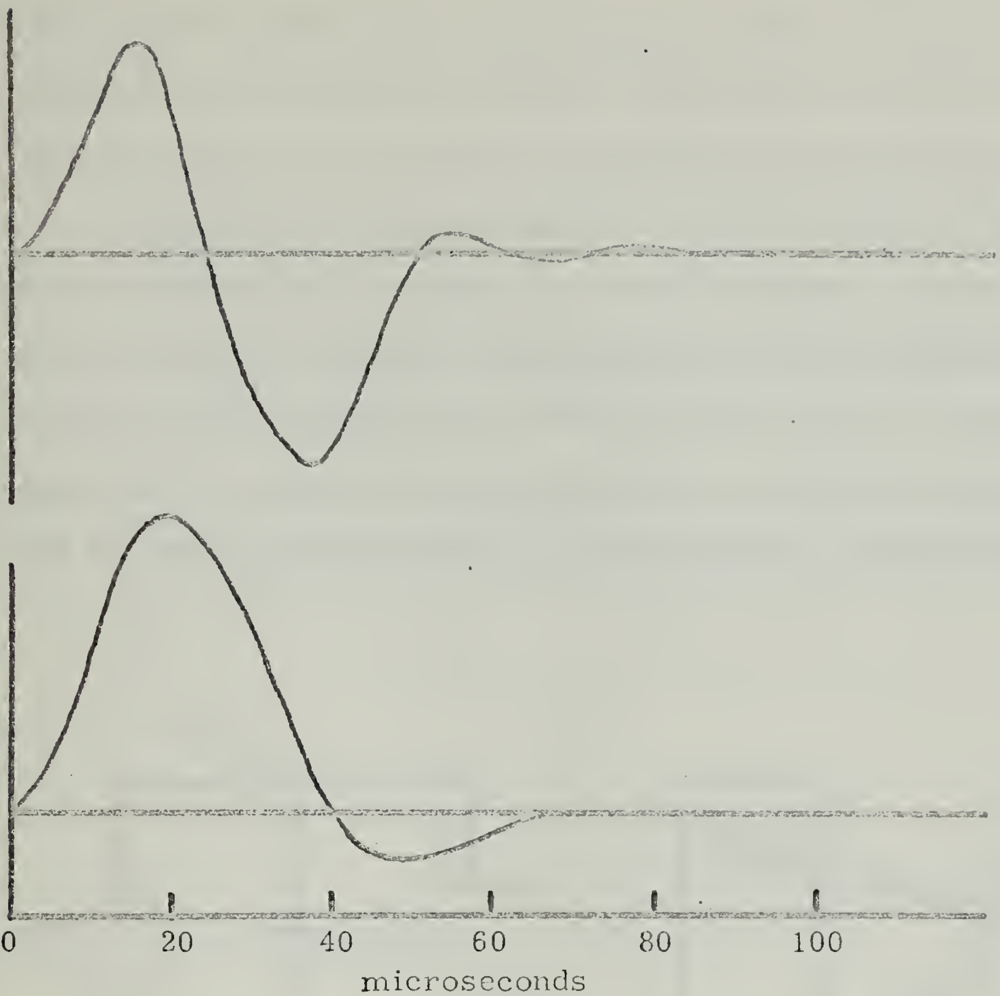

Fig. 14a,b. Acoustical doublet in air and its integral. Magnitude scale arbitrary.

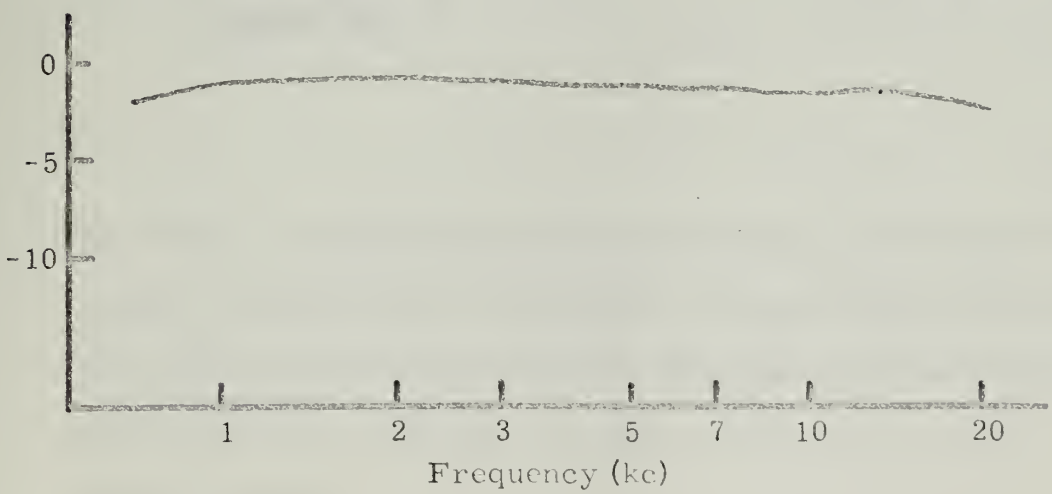

Fig. 14c. Magnitude of spectrum of Fig. 4b. See Appendix D for method used to find frequency transform.

the length in air of a 50 µs duration spark sound is less than one inch, the experiments became essentially independent of environment and it was not necessary to conduct the experiments in an anechoic chamber.

The apparatus used to generate the spark sound (see Fig. 15) is essentially that used by Dodds,[6] but with a change in electrode size, shape, and gap to produce a waveform more closely approximating a doublet. This modification was done by trial and error, measuring the spectrum of a typical spark each time by a method described in Appendix D. As was shown in Fig. 14, the waveform produced by this spark

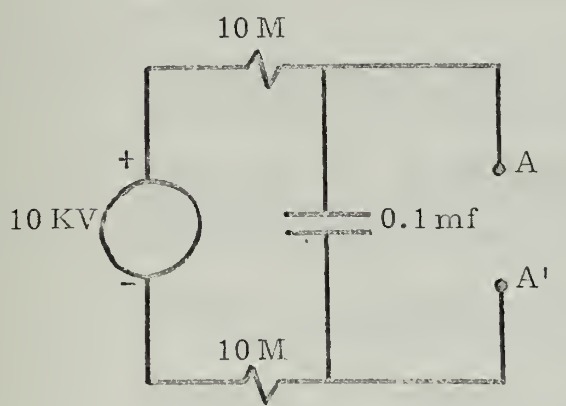

Fig. 15a. Spark generator. From Dodds'[5] Fig. 1.

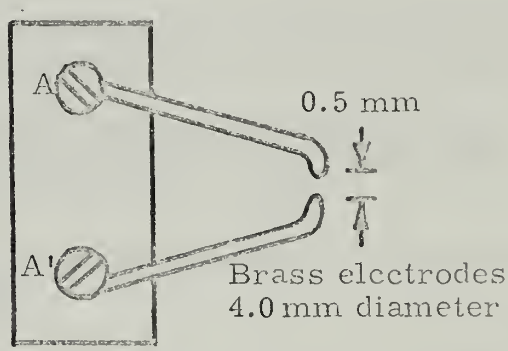

Fig. 15b. Spark gap.

gap is that of a doublet from 20 cps to 20 kcps, which is the frequency range of interest here. In operation, the spark generator produced a spark about every three to four seconds. The sound pressure level as measured by the microphone system was 120 to 135 db with the spark six feet from the microphone.

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